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Effect of Nitrogen Dilution on the Lean Blowout Limit and Emissions of Premixed Propane/Air Swirl Flame

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Graphical abstract

Abstract

The effects of nitrogen dilution on propane/air flame and emissions was investigated using a model gas turbine type swirl flame burner. The burner consists of a six-vane axial swirler and a combustor wall made from quartz tube. Nitrogen was diluted at 5%, 10% and 15% by volume of the total main air flow rate with propane/air mixture at the burner plenum prior to combustion at atmospheric condition. Direct flame imaging was performed using a digital camera to observe the flame shape, intensity and lean blowout phenomenon of premixed nitrogen-diluted propane/air flames. The result shows that nitrogen addition to propane/air flame reduces flame intensity and lean blowout limit, making the nitrogen-diluted flames more susceptible to blowout. Emissions results show that NO_x reduce with the increase of nitrogen dilution rate, while the effect on carbon monoxides and unburned hydrocarbons are insignificant.

Keywords: Nitrogen-dilution, propane, swirl, NO_x, emissions

1.0 INTRODUCTION

Increased environmental awareness has led research to focus on the design of clean combustion devices and low emissions combustion methods. In modern gas turbine, innovative combustion chambers are designed and operated with advanced low emission operation techniques such as lean, premixed and prevaporised (LPP) and dry low emissions (DLE) combustion mode. The goal is to reduce NO_x emissions to the level within the regulation limit.

The technique of exhaust gas recirculation (EGR) used to control emissions has previously been introduced. In transportation sector, EGR has proven to effectively lower NO_x emissions for diesel engine [1], although smoke emissions were shown to increase [2]. The reduction of NO_x from EGR method is attributed to the lowering of flame temperature and oxygen concentration in the combustion chamber. Maiboom *et al*. [3] investigated the effect of EGR on combustion, NO_x and particulate matter emissions using a diesel engine at part load conditions. The result shows that EGR at low load conditions drastically reduces NO_x and particulate matters but increases brake-specific fuel consumption. The EGR technique is also extensively applied in direct injection gasoline engine to improve fuel economy [4-6]. Sasaki *et al.* [7] reported that an increase of EGR rate in a direct injection gasoline engine results in the reduction of unburned hydrocarbon (UHC) and NO_x emission. The burning rate at the initial stage was reduced while late phase combustion was enhanced.

Application of EGR in gas turbine has been conducted and promising results were shown. Mitsubishi Heavy Industries (MHI) developed a high pressure gas turbine test rig to test the effect of EGR. The result shows that the NO_x and CO concentration obtained from the test was lesser than 50 ppm and 10 ppm respectively [8]. Røkke and Hustad [9] utilised a 65 kW gas turbine combustor to show that NO_x emissions was reduced when EGR gas obtained from the exhaust is injected to the entry port of a gas turbine. Krishnan *et al.* [10] developed a predictive correlation that shows the estimated NO_x emissions with respect to the amount of EGR used under certain operating conditions. Cameretti *et al.* [11] demonstrated that an external EGR circuit can effectively reduce NO emission without penalising combustion efficiency via computational study.

The effect of nitrogen dilution on gaseous flame have been performed by several groups. At laboratory scale, Khalil *et al.* [12] investigated the emissions of NO_x and CO emissions using methane and nitrogen-diluted methane flame. The results showed that nitrogen seeded fuel decreases NO_x emission as N_2 acts as inert energy sink that decreases the overall caloric value of the mixture. As a result, temperature in combustor decreases and subsequently leads to the decrease in NO_x. On the other hand, CO increases due to the decrease in residence time available for complete oxidation into CO_2. At fundamental level, the effect of nitrogen dilution on propane/air at elevated temperature and pressure has been performed [13]. By using a constant pressure combustion chamber, an outwardly expanding nitrogen-diluted propane/air flame was imaged by Schlieren photography and high speed camera. The measured flame speed agreed well with the predicted computational value. The hydrodynamic instability of the flame was shown to reduce with the increase of nitrogen dilution ratio.

In the present study, the potential of using inert gas (nitrogen) dilution technique as a mean to control NO_x emissions for a model gas turbine combustor is investigated. The effect of nitrogen dilution emulating the exhaust gas recirculation on the flame and emissions are investigated as a function of equivalence ratio at atmospheric conditions.

2.0 EXPERIMENTAL

2.1 Burner and Flow Delivery System

The present swirl burner consists of an axial swirler and a quartz tube placed concentrically with the burner outlet as combustor wall. The swirler consists of six straight vanes fixed at the angle of 45° from the centerline axis. The calculated geometrical swirl number, S_N, is 0.84 based on the equation [14]:

$$S_N = \frac{2}{3}\left[\frac{1-(D_h/D_s)^3}{1-(D_h/D_s)^2}\right]\tan\theta \qquad (1)$$

where D_h and D_s represent the swirler hub diameter and the swirler diameter respectively, and θ is the vane angle orientation from the centreline axis. The swirl number of 0.84 indicates that sufficiently strong swirl flow can be generated to stabilise the flame [15, 16]. The quartz tube forms a combustor wall of 400 mm in length and 112 mm internal diameter at the dump plane region. The burner body and plenum are made from stainless steel. In order to form a premixed swirl flame stabilised at the burner outlet, propane gas (Megamount; 99.5% purity) was used as gaseous fuel to premix with air at the plenum of the burner at room temperature. This is prior to delivery to burner outlet via flow passages of the swirler. The main air flow and gaseous fuel were supplied and regulated by two mass flow controllers (Sierra; Air: model C50M, Propane: model C50L), which both delivers the full scale accuracy of ± 1%. The nitrogen flow is supplied via a flow meter (Key instruments; MR3000; ± 5% uncertainty). The schematic of the burner and flow delivery system is shown in Fig.1.

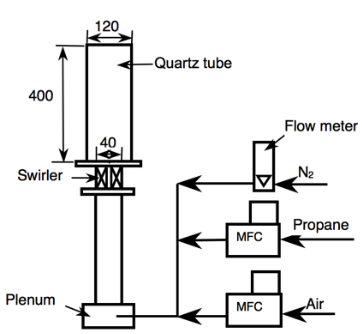

Figure 1 Schematic of swirl burner and flow delivery system

2.2 Operating Conditions

The premixed flames were established with air mass flow rate fixed at 2.34 g/s (equivalent to 120 l/min), while the propane fuel mass flow rate is varied according to the required equivalence ratio. Table 1 shows the operating conditions for emissions measurements.

Table 1 Flow rates of air and fuel at varied equivalence ratio

ø	$\dot{V}_{air}$ (l/min)	$\dot{m}_{air}$ (g/s)	$\dot{V}_{fuel}$ (l/min)	$\dot{m}_{fuel}$ (g/s)
0.8	120	2.34	3.97	0.12
0.9	120	2.34	4.46	0.13
1.0	120	2.34	4.96	0.15
1.1	120	2.34	5.46	0.16
1.2	120	2.34	5.95	0.18

The effect of nitrogen dilution on the air/fuel mixture is performed by supplying nitrogen to the plenum for premixing with air and fuel prior to combustion at the burner outlet, based on the dilution rate defined by:

N_2 dilution rate (%) = (volumetric flow rate of N_2/ main volumetric air flow rate) x 100%

Dilution of fuel/air mixture with nitrogen is performed at 5%, 10% and 15% by volume of the total main air flow rate. Table 2 shows the N_2 flow rates at different dilution rate premixed with the undiluted baseline case of equivalence ratio ø = 1.0. The effective equivalence ratio $ø_{eff}$ after the nitrogen dilution with the mixture is shown. For direct flame imaging and emission measurements, the baseline flames are established with the air mass flow rate of 2.34 g/s. Flame imaging is performed using a digital single-lens reflex camera (Canon: EOS 5D).

Measurement of the post-combustion gases was performed at the burner exit of a confined combustor using an exhaust gas analyser (EMS 5002). The sampling probe (6 mm diameter) from the gas analyser was placed 10 mm inwards from the combustor outlet to sample across the burner centerline. Sampling was performed at 7 spatial locations spaced at 16 mm, with each measurement recorded after steady-state readings were obtained. The emissions (resolution) measured were NO_x (1 ppm), CO (0.01 %), CO_2 (0.1 %) and UHC (1 ppm).

3.0 RESULTS

3.1 Effect of Nitrogen-Dilution On Lean Blowout Limit

The effect of nitrogen-dilution on the flame blowout limit is determined as a function of main air flow supply. The flame is first established and stabilised at ø = 0.8. Subsequently, the fuel flow rate is reduced gradually until the flame blows out completely. The final fuel flow rate at which the flame extinguished is recorded and the equivalence ratio is calculated. Two sets of lean blowout limit tests were conducted, i.) propane/air and ii.) propane/air/0.094 g/s (~5 l/min) N_2 dilution rate. Figure 2 shows the lean blowout limit for the range of air flow rate between 1.17 g/s and 3.9 g/s (air volumetric flow rate of 60 - 200 l/min).

Lean blowout limit for undiluted propane/air mixture is around ø = 0.5 for the range of main air flow rate between 1.56 - 3.9 g/s (80 - 200 l/min). For air flow rate less than 1.56 g/s, lean blowout limit is $ø = 0.6$. Further reduction of main air flow below 1.17 g/s (60 l/min) results in the formation of unstable flame due to insufficient strength of swirl flow to sustain and stabilise the flame. The region above the limit of lean blowout indicates the operational range of the burner. Dilution with 0.094 g/s (5 l/min) of nitrogen in propane/air mixture results in the operational limit to be narrowed by around $ø = 0.05$ in general. For flow rates between 1.75 - 2.92 g/s (90- 150 l/min), the lean blowout limit is around $ø = 0.55$. For main air flow rate of <1.75 g/s (90 l/min), the lean blowout limit is between $ø = 0.65$-0.7. The dilution with nitrogen results in leaner mixture with less oxygen for reaction with fuels. Figure 3 shows the instantaneous images of blowout event. Prior to flame blowout, the flame is detached and stabilised away from the burner outlet. The reduction of fuel results in the unsustainability of the flame, where insufficient post combustion product is recirculated back to the flame root. Subsequently, the flame is convected downstream by the main air flow.

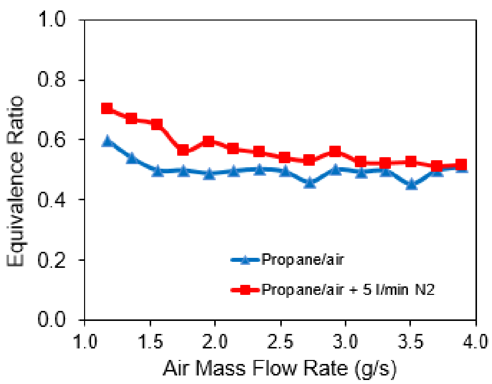

Figure 2 Lean blowout limit for propane/air and propane/air/0.094 g/s N_2 dilution at different main air flow rate

Direct flame images of premixed propane/air swirl flame are shown in Fig. 4. The baseline cases without nitrogen dilution at equivalence ratios spanning from lean to rich flames are shown in Fig. 4a. Flames with nitrogen dilution at 5%, 10% and 15% are shown in Fig. 4b, 4c and 4d, respectively, with the effective equivalence ratio indicated underneath the flame images. For the baseline lean flame of $ø = 0.8$, the flame is bluish with some instability observed as the flame root is not attached to the burner outlet. Addition of nitrogen into the flame results in even leaner equivalence ratio. The flame becomes unstable and more susceptible to blowout as the flame is further detached from the burner.

Swirl flame at ø□= 0.9 is relatively more stable compared to ø□= 0.8. The baseline fuel without N_2 dilution shows high flame intensity with reddish post reaction zone flame while nitrogen-diluted flames show reduced flame intensity, as the peak temperature is expected to decrease. As the equivalence ratio shifts towards stoichiometric and rich-burning region, the flame burns more vigorously with good flame stability. The visually observed reddish-orange post flame indicates the presence of soot. Nitrogen dilution with mixture at ø□= 1 results in leaner equivalence ratio, and hence the N_2-diluted flames are in the region of lean-burning. Thus, less visible reddish sooty flame is observed. Rich-burning flames ($ø > 1$) show green-bluish intense flame reaction zone and strong reddish-orange sooty post flame downstream. Addition of nitrogen into rich flame reduces flame height as the sooty flame length is reduced.

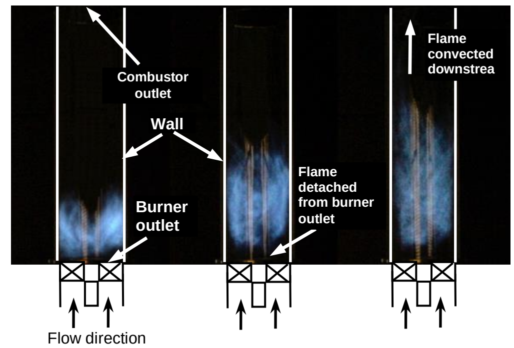

Figure 3 Instantaneous images of lean blowout phenomena for a swirl flame. The flame is detached from the burner outlet and convected downstream towards the combustor outlet

3.2 Emission Profiles Across Burner Outlet

Figure 5 shows the emission profiles of NO_x obtained radially across the combustor outlet for propane/air flames at different nitrogen dilution level. The profiles are obtained at the equivalence ratio of $ø = 0.8$, 1.0 and 1.2. The measurements were taken under steady state condition at the burner outlet. The x-abscissa denotes the radial position non-dimensionally across the burner outlet in $2r/D$, where r is the radial position from centreline and D is the diameter of the combustor outlet (112 mm). For lean mixtures, NO_x emissions are generally low and the profiles are flat at the burner outlet. For stoichiometric and rich mixtures, the local emissions near combustor wall show distinct values, especially for 0% and 5% nitrogen dilution, indicating inhomogeneous distribution of NO_x species at the combustor outlet. This could be attributed to the effect of flow field distribution within the combustor. The baseline case of 0% nitrogen dilution shows that ø□= 1 exhibits the highest level of NO_x emission compared to lean and rich burning cases. An addition of 5% nitrogen dilution results in lower NO_x emission comparable to 5% N_2-diluted rich flame ($ø = 1.2$). The emission profiles for ø□= 1.0 and $ø = 1.2$ at 15% nitrogen addition show rather similar profiles.

3.3 Effect of Nitrogen Dilution On Emissions

The global emission values are derived by averaging the spatial values obtained at the combustor outlet. Four emissions are shown in Fig. 6, namely NO_x, CO, UHC and CO_2 as a function of effective equivalence ratio at different N_2 dilution rate. The baseline flames without N_2 dilution show an increase of NO_x emissions as the mixture progress from lean to stoichiometric condition. NO_x emission peaks at stoichiometric mixture before dropping at rich-burning region. Peak NO_x emission is shifted towards the globally lean burning regions as nitrogen dilution increases. Dilution with N_2 at 5% reduces NO_x emission distinctively, especially for the stoichiometric mixture. Further N_2 dilution at 10% and 15% by volume reduces NO_x by almost 50% compared to baseline case at $ø = 1.0$. It is noted that addition of nitrogen in 10% by mass over the total air mass can achieve about50% reduction in NO_x emissions, indicating the effectiveness of using exhaust gas recirculation as a mean to

Table 2 Different nitrogen dilution rate with propane/air at $ø = 1$

$ø$	N_2 dilution rate (%)	$\dot{V}_{air}$ (l/min)	$\dot{m}_{air}$ (g/s)	$\dot{m}_{fuel}$ (g/s)	$\dot{V}_{N_2}$ (l/min)	$\dot{m}_{N_2}$ (g/s)	ϕ_{eff}
1.0	0	120	2.34	0.15	0	0	1.00
1.0	5	120	2.34	0.15	6	0.11	0.95
1.0	10	120	2.34	0.15	12	0.23	0.91
1.0	15	120	2.34	0.15	18	0.34	0.87

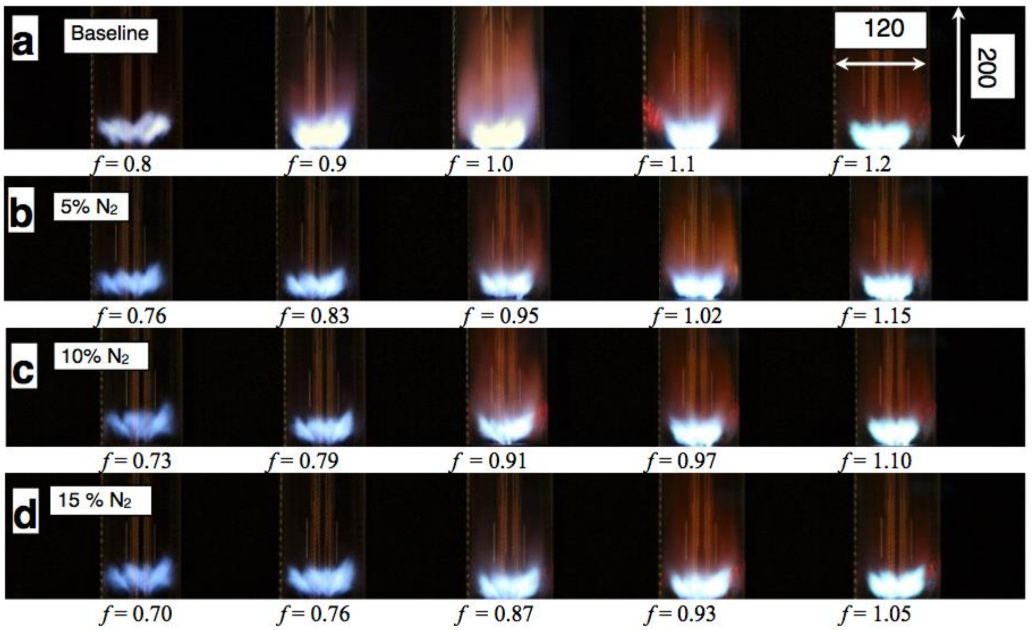

Figure 4 Direct flame images of propane/air at different equivalence ratio at (a) 0% (b) 5% (c) 10% and (d) 15% nitrogen dilution rate. The baseline flames (a) are established based on the operating conditions shown in Table 1

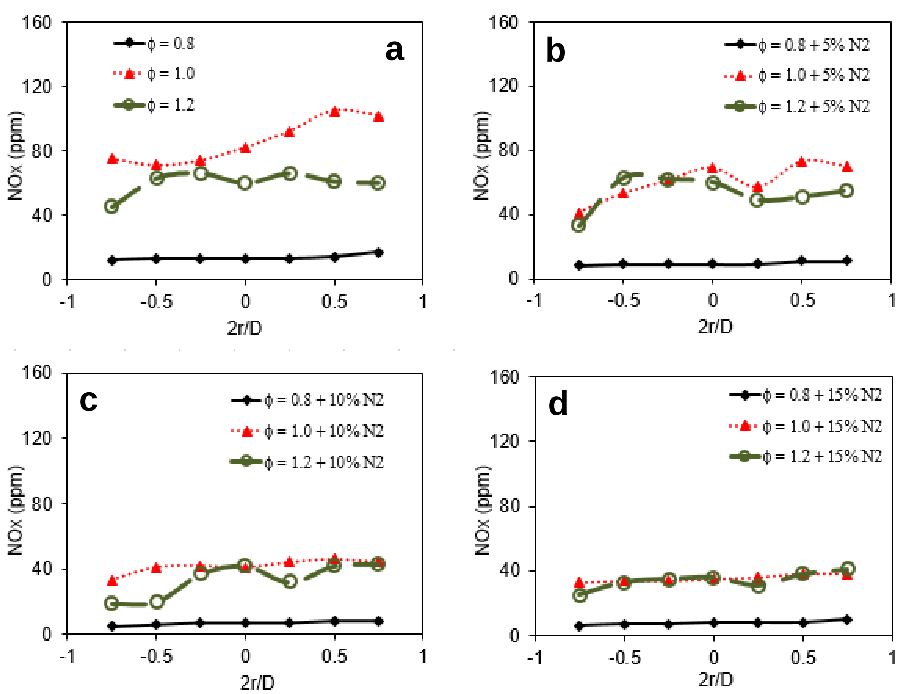

Figure 5 NO_x emissions profiles at burner outlet for (a) 0% (b) 5% (c) 10% and (d) 15% N_2-diluted propane/air flames at different equivalence ratios

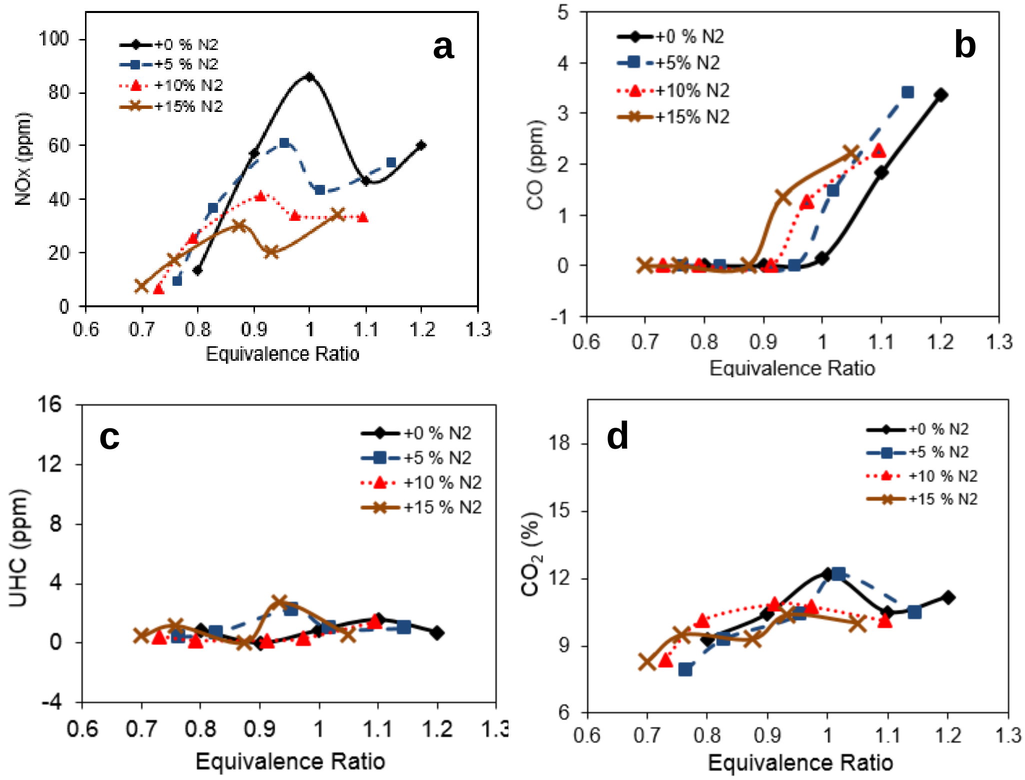

Figure 6 Emissions of (a) NO_x , (b) CO, (c) UHC and (d) CO_2 as a function of effective equivalence ratio operating at different nitrogen dilution level

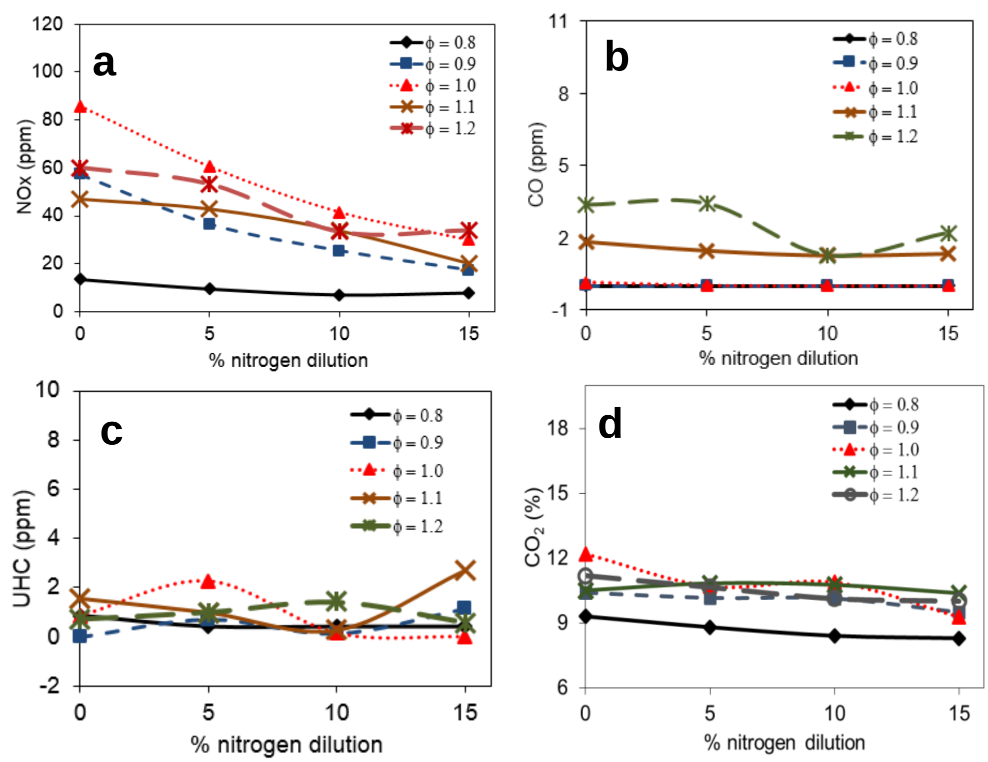

Figure 7 Emissions of (a) NO_x (b) CO (c) UHC and (d) CO_2 as a function of nitrogen dilution percentage at different equivalence ratio

control NO_x. The addition of nitrogen increases the mixture heat capacity, lowers the flame temperature and hence inhibits the production of thermal NO_x. In the rich burning region, nitrogen-diluted flame shows in general lower NO_x production than the baseline case.

CO emissions are almost zero at lean condition but increase slightly when approaching stoichiometric and rich region. The values for all cases tested were within 5 ppm, typically for the range of ϕ = 0.9 - 1.2. The low emission of CO is attributed to the nature of premixed combustion. At lean combustion, fuel is completely oxidized. Although CO can be produced at high temperature in stoichiometric and rich reaction region, the long residence time available for CO to be oxidized into CO_2 within the combustor (40 mm in length) results in low CO emission value. Addition of N_2 into the mixture results in slight increase of CO (within 2 ppm).

Emission of UHC is less than 3 ppm for the range of equivalence ratios and nitrogen dilution ratio tested as shown in Fig. 6c. This indicates that combustion in the chamber is rather complete. Higher reading of UHC is expected at the rich combustion region, but the long combustion tube provides sufficient residence time for UHC to be fully oxidized. The effect of nitrogen dilution on UHC emissions is non-obvious. Figure 6d shows the overall CO_2 emissions increase as the equivalence ratio shifts to the stoichiometric. Beyond that CO_2 emissions start to plateau. This corresponds to the high CO emissions at the rich region where insufficient oxygen is available to convert CO into CO_2. The effect of nitrogen on CO_2 is not obvious in the lean region, but 10% and 20% N_2 dilution reduces the emission of CO_2 in the stoichiometric and rich region.

Emissions as a function of nitrogen dilution rate are shown in Fig. 7. N_2 dilution has the most significant impact on NO_x emission, in particular 15% N_2 dilution rate shows almost 50% NO_x reduction for ϕ = 0.9, 1.0 and 1.1. Nitrogen dilution shows minor NO_x reduction for lean mixture of ϕ = 0.8. There is no clear trend of effect of nitrogen dilution on CO and UHC. For CO_2, the overall trend shows slight reduction of CO_2 with respect to the increase of nitrogen dilution rate.

4.0 CONCLUSION

The effect of nitrogen dilution on propane/air flame is investigated over a range of equivalence ratio under reacting swirl flow conditions. The lean blowout limit is reduced with nitrogen dilution as flame instability is enhanced with reduced amount of oxygen. The flame intensity is reduced with the addition of nitrogen. Emission measurements show that reduction of NO_x corresponds to the increase of nitrogen dilution rate. The addition of 10% nitrogen by mass into propane/air mixture results in about 50% reduction of NO_x for ϕ = 1.0. The reduction of NO_x is mainly due to the lowering of the flame temperature that inhibits the formation of thermal NO_x. However, the effect of N_2 on CO and UHC emissions are insignificant over the range of equivalence ratio tested.

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